Corsica: Integrated Simulations for Magnetic Fusion Energy

FOR years, magnetic fusion energy (MFE) scientists have dreamed of an integrated, easy-to-use, and comprehensive family of computer codes that would simultaneously simulate all of the important physics processes that take place in a magnetic fusion reactor. Such a package would be valuable for enhancing the understanding of the extremely complex phenomena observed in experiments. It would also provide a tool to optimally design future MFE experiments.

Although this goal of virtual experiments is still years away, researchers at Lawrence Livermore have made important advances in developing such a comprehensive simulation package. In designing such a code, called Corsica, they have developed techniques to efficiently couple separate physics processes. These techniques plus continuing advances in high-performance computer hardware and software offer the prospect of achieving the goal. Corsica is only one part of a widespread effort, evident throughout Livermore research programs, to simulate to unprecedented levels of accuracy the physical phenomena taking place on scales ranging from atomic particle interaction to global weather patterns.

In fusion, two light nuclei (such as hydrogen) combine into one new nucleus (such as helium) and release enormous energy in the process. One approach to fusion uses a powerful magnetic field to confine a plasma (a gas consisting of charged ions and electrons), generating energy in a controlled manner. To date, the most successful approach for achieving controlled fusion is in a donut-shape configuration called a tokamak.

Future experimental facilities will be much larger than today's research tokamaks and much more expensive, costing as much as several billion dollars each. Although advanced simulations will never replace experimental work, they are needed to optimize the design of future tokamaks and experiments, which will save millions—maybe billions—of dollars. Simulations are also needed to analyze and optimize alternative concepts to the tokamak, such as the small spheromak device that Livermore is now constructing. Scientists consider such simulations essential to resolving several important physics issues, such as how to structure the magnetic fields to produce the maximum pressure and what processes drive electric currents and magnetic fields.

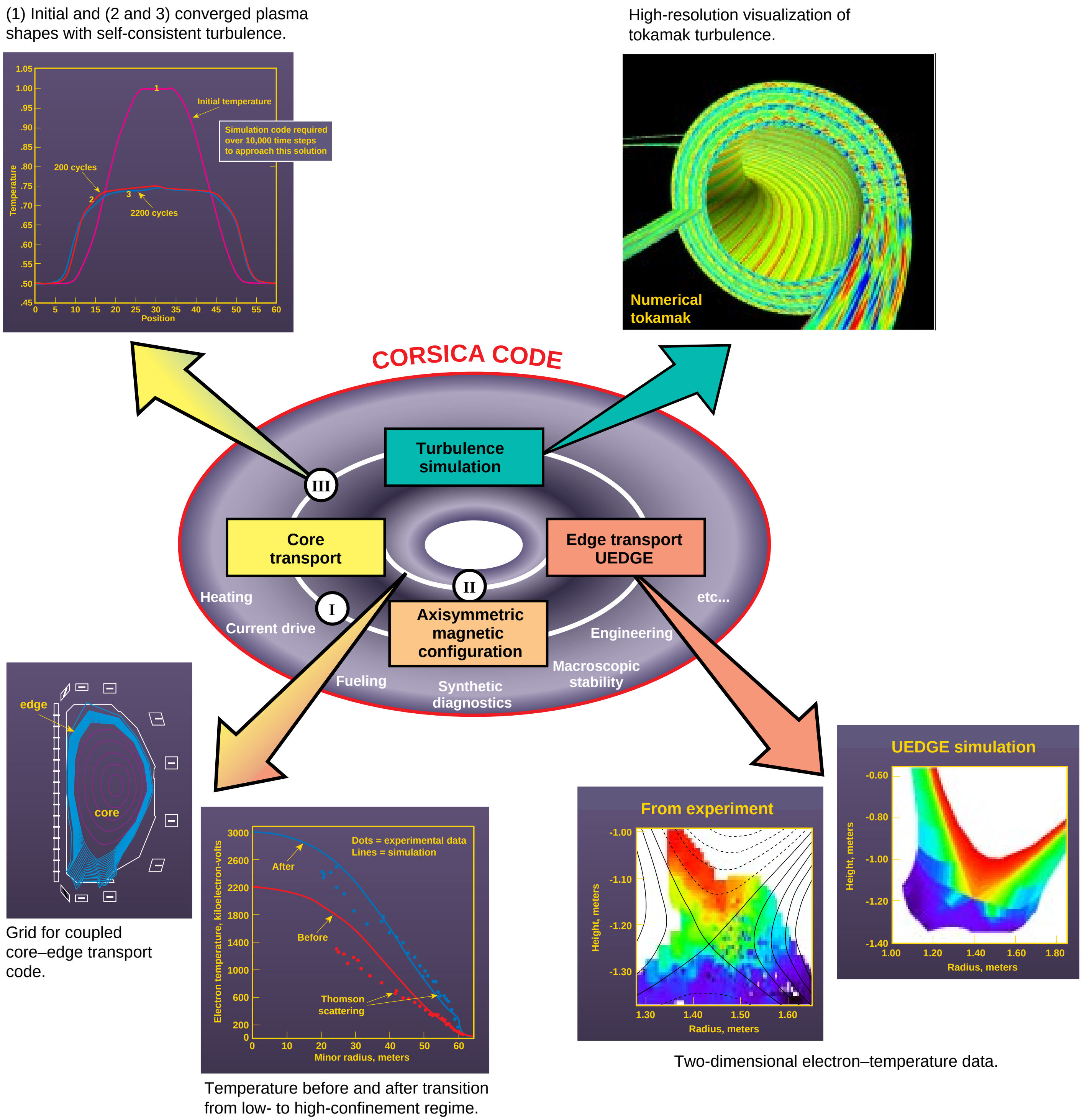
The Need for Integration

"Simulations of individual phenomena—physics 'packages'—now exist as essential tools for analyzing fusion experiments," says Livermore's Keith Thomassen, Deputy Associate Director for MFE. Phenomena such as the equilibrium of the plasma, turbulent transport, stability, and heating, are examples of such processes and are interdependent. Thus, codes that simultaneously describe all these phenomena have these packages "hard wired" together, and the codes are extremely complex. A contributor to this complexity is the disparate time and spatial scales of these phenomena.

MFE processes span a wide range of time scales, from turbulent fluctuations on the microsecond scale to transport processes with scales of seconds to hours. For example, particle velocities parallel to the magnetic field are orders of magnitude greater than those moving perpendicular to the magnetic field. Additionally, MFE models must reflect a range of spatial scales that extend, for example, from the spiral orbit size of an electron to the several-meter-wide tokamak device.

David Baldwin, vice president for fusion research at General Atomics (GA) in San Diego, was Associate Director for Energy Programs at Livermore in the early 1990s when Corsica development began. "The MFE community had done a very good job in developing discreet physics packages but had little experience integrating them. We wanted to provide that capability for the first time but in modular units," he says, "so that, as individual physics packages improved, they could be exchanged. But the entire code would not have to be rewritten."

The inspiration for Corsica, says Baldwin, was Livermore's long-standing LASNEX integrated code for laser fusion that simulates interactions between laser light and its targets. He also notes that Corsica's objective of integrating all the physics phenomena is analogous to that of the Accelerated Strategic Computing Initiative (ASCI), the Department of Energy's effort in the Stockpile Stewardship Program to develop full-system simulations running on new generations of high-performance computers. Indeed, several Livermore Corsica developers are also contributing to ASCI.



The Corsica magnetic fusion simulation code is a prototype for an integrated simulation that would solve models for all aspects of tokamak operations. Roman numerals in the center graphic indicate successive Corsica code releases; images demonstrate their capabilities.

Corsica I, released in 1994, flexibly coupled one-dimensional calculations of particle, energy, and magnetic-flux transport in the core, or confined region, of the plasma to a calculation of a two-dimensional magnetic configuration. Corsica II, released for testing by sophisticated users in 1995, coupled the one-dimensional core transport calculation to a simulation of the two-dimensional "edge" where magnetic-field lines intersect material surfaces.

A still more advanced version, Corsica III, is being developed as funding permits. Its ambitious goal is to couple the evolution of the fusion process to plasma turbulence models for a more comprehensive simulation. The turbulence coupling effort benefits from the sheer computing power of the newest supercomputers as well as from the experience in turbulence of Livermore's MFE theory group. The group participates in the Department of Energy's Numerical Tokamak Turbulence Project, designated a DOE grand challenge.

By handling a wide range of physics with disparate time and spatial scales, Corsica permits more complete modeling of toroidal (donut-shaped) plasmas and other magnetic fusion concepts than previously possible. As a result, the software has been adopted at both national and international research sites. For example, Corsica is used to model plasma confinement in the DIII-D experimental tokamak at GA, where a team of Lawrence Livermore scientists is working. Corsica was used on simulations of the Tokamak Fusion Test Reactor that operated at the Princeton Plasma Physics Laboratory. Corsica has also been used to model the design for the International Thermonuclear Experimental Reactor and Livermore's Sustained Spheromak Physics Experiment.

Corsica Keys on Flexibility

Livermore physicist Tom Casper uses Corsica to replicate experiments conducted on GA's DIII-D tokamak. He says Corsica helps him obtain a better understanding of past experiments and plan future experiments. He points to the code's flexibility as one of its strong suits. "I can modify the code and manipulate variables, capabilities we don't find in other codes."

In addition, Casper notes that budgets and space constraints limit the number of diagnostic instruments that can be used on the DIII-D tokamak. With Corsica running on a powerful workstation, Casper can add as many so-called synthetic diagnostics as he desires and thereby gain a more complete picture of an experiment.

Corsica's flexibility is provided in part by BASIS, a code steering system developed by Livermore computational scientist Paul Dubois in the 1980s. BASIS also served as the underlying system for LASNEX. Leaders of both the Corsica and ASCI programs have recently chosen Python as the successor to BASIS because of its greater flexibility and its ability to run on many different computers.

Baldwin says Corsica today is "darn good" but still far from the complete simulation code that he and other leaders of the MFE community envision. For that to happen, he says, other major MFE centers need to join forces with Livermore and GA and integrate their own specialized codes, as well as tap the experience of other comprehensive code efforts such as ASCI.

"We want to create a national project that benefits from our experience here," says Ron Cohen, leader of Livermore's MFE theory and computation program. Cohen and others have proposed a "national transport code," a modern code that would draw upon the concepts in Corsica and the vast wealth of physics simulation "building blocks" available nationally. Cohen notes that because the family of MFE simulation codes was created at different research centers in different software languages and on different computers, the effort to modify them and then combine them into a seamless, integrated package will demand strong cooperation among researchers.

In the meantime, Livermore scientists are collaborating with colleagues at GA to combine the best features of GA's transport code with those of Corsica. They hope to carry out their project within the context of the national transport code project.

If the national effort is successful, users will be able to select from many different physics "plug-in" modules to build custom simulations of various—or all—aspects of a magnetic-fusion experiment (tokamak or other configuration). The integrated code would also allow a user to modify experimental conditions and theory parameters or even whole models in real time, without having to use elaborate commands.

"We want to have an integrated, 'living' code that keeps changing and growing as computer capabilities and ideas advance," says Cohen. While it could never serve as a substitute for an actual experiment, such an integrated simulation would undoubtedly save money by enabling better-designed and more aggressive experiments. "By combining data from this code with hardware experiments, we'd get the most out of the research dollar," he says.

— Arnie Heller

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Device Assembly Facility: New Facilities for Handling Nuclear Explosives

AS the 18-wheeler slowly eased up to the loading dock under a heavily armed escort, massive steel doors opened from the inside of a partially buried structure. An announcement was broadcast over the public address system alerting specially trained personnel of the arrival of a safe and secure transport vehicle. This special big rig is part of a fleet used by the U.S. government to transport nuclear weapons or weapon components from one secure site to another. Technical specialists stood ready to unload the shipment.

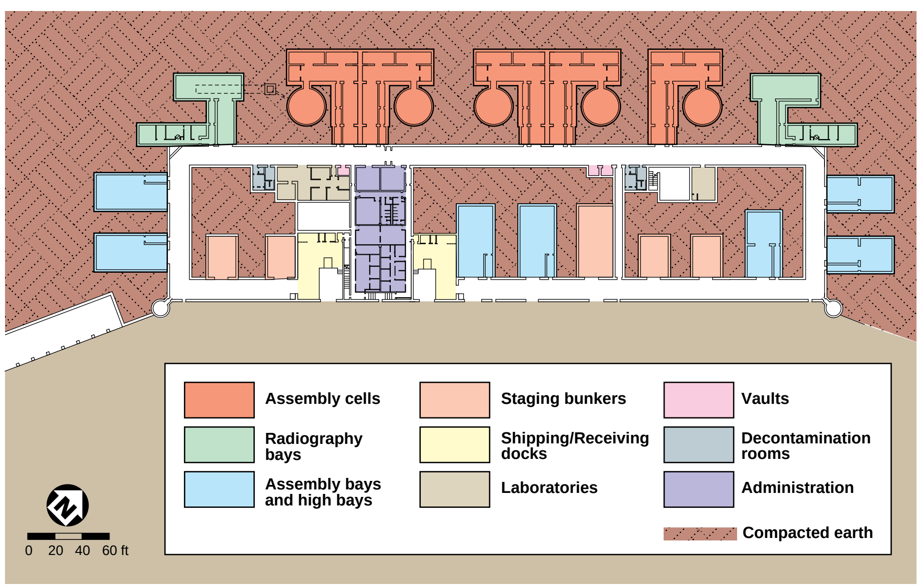
The scene of this activity at the Nevada Test Site is the Department of Energy's newest facility, located 90 miles northwest of the famous Las Vegas strip in a remote part of the Nevada desert. The recently opened Device Assembly Facility, or DAF, offers one of the safest, most secure locations anywhere in the U.S. weapons complex to conduct nuclear explosive operations. Other than the Pantex Plant in Amarillo, Texas, the Nevada Test Site is the only location in the country where special nuclear material such as plutonium can be mated with high explosives.

Under a unique arrangement with the Department of Energy, Lawrence Livermore and Los Alamos national laboratories are designated joint operators and users of the facility. Since the facility's inception, the laboratories have collaborated on every aspect of the facility—including its design, construction, certification, management, and use. Management responsibility is rotated between the laboratories, nominally every two years. "This is truly a joint-lab facility," explains James Page, DAF startup team leader for Livermore. "We share common procedures and integrated hazards analyses and operate with a management team composed of personnel from both laboratories." In contrast, nuclear explosive operations at the Nevada Test Site in the past were conducted in two separate facilities according to Laboratory affiliation.

Adapting to Challenges

DAF dates from the mid-1980s, when the weapons laboratories were engaged in active nuclear testing. As with many aspects of the Department of Energy's weapons program, DAF has been adapted to a changing environment brought about by changes in national nuclear testing policy. Designed and built for the purpose of assembling the two laboratories' nuclear test devices prior to placing them underground for testing, the new facility retains its original name. Its mission, however, has evolved since the nuclear testing moratorium began in October 1992.

Instead of the underground test assembly work for which the facility was originally intended, DAF will accommodate other hands-on activities involving high explosives, special



Schematic of the main floor of the Device Assembly Facility at the Nevada Test Site.

nuclear material, nuclear weapon components, and nuclear devices. These projects, an integral part of DOE's Stockpile Stewardship Program, will include assembly work to support new subcritical (no-nuclear-yield) experiments being conducted nearby as well as stockpile maintenance activities, such as enhanced surveillance technology development and personnel training. These activities will provide necessary data to help maintain the nation's nuclear deterrent. Future use could also include DOE activities to maintain a nuclear emergency response capability.

Anatomy of the Facility

In a bunker-style arrangement, DAF is a collection of 30 individual steel-reinforced concrete buildings connected by a rectangular racetrack corridor. The entire complex, covered by compacted earth, spans an area the size of eleven football fields (see schematic drawing on p. 23). Because the buildings were designed to accommodate potentially hazardous operations, they meet the most stringent set of safety regulations.

Explains Page, "This facility was intended to provide the safest possible environment for conducting hands-on operations involving special nuclear material and high explosives. The DAF design incorporates the most modern safety and security features in the weapons complex."

The DAF multistructure occupies about 10,000 square meters of usable floor space and consists of operational buildings for work involving high explosives and special nuclear material and support buildings for laboratories and offices.

Most isolated of the operational buildings are five assembly "cells" for activities involving uncased conventional high explosives and special nuclear material. Four high bays and three assembly bays provide facilities for less hazardous operations, such as those involving uncased insensitive high explosives. When radiography is required to verify the integrity and spatial relationships of objects, a 9-megaelectron-volt, movable-beam, linear accelerator is available in one of two radiography bays. Five staging bunkers provide ample space for interim storage of nuclear components or high explosives. Finally, all materials packages arrive or depart DAF through either of two shipping and receiving bays.

The support buildings include three small vaults for storing small quantities of high explosives or special nuclear material; two decontamination areas; and an administration area containing office space, a conference area, personnel changing and shower rooms, and a machine shop. In addition, two buildings provide laboratory space: one for conducting component, instrumentation, and environmental testing and the other for controlling remote operations of an adjacent assembly cell.

The bunker-style Device Assembly Facility has about 10,000 square meters of floor space in its 30 steel-reinforced concrete buildings.

Blast Protection and Containment

To provide the utmost protection for personnel working within the facility and for the environment, DAF employs several state-of-the-art safety features. Chief among them are blast doors on all operational buildings to mitigate the propagation of an accidental explosion, blast-actuated valves on the ventilation system to prevent the spread of contamination, special ventilation features such as zoned air-supply systems and high-efficiency particulate air filters, and the unique design of the assembly cells.

Indeed, the assembly cells are whimsically called "gravel gerties," after a 1950s Dick Tracy comic-strip character because the roof is overlaid with nearly 7 meters of gravel, said to resemble the original Gravel Gertie's thick curly gray hair. Modeled after the structures at Pantex, where hands-on assembly and disassembly of U.S. nuclear weapons take place, they provide the maximum environmental and personnel protection in the event of an inadvertent high-explosive detonation. The cells are designed to absorb the blast pressure from a detonation of up to 192 kilograms of plastic-based explosives (equivalent to 250 kilograms of TNT, or approximately one-fifth of the explosive energy released in the World Trade Center bombing). Should a detonation occur, the gravel gertie would minimize environmental release of nuclear material and propagation of the event to other areas in the facility.

"Although it is extremely unlikely that the cells would ever be required to perform to their full potential," says Page, "their design provides the extra assurance necessary for moderately hazardous activities, such as weapon assembly and dismantlement and some processes for monitoring changes due to aging. In addition, the assembly cells could be used to disable nonstandard explosives, such as a clandestine nuclear device."

A National Resource

The design of the facility, its remote location, and its safety features make DAF well suited to address new national challenges—both predicted and as yet unforeseen—in maintaining the nuclear stockpile. Like Livermore's Laser Programs, started in the 1960s to research electrical power but now studying fundamental physics issues as well, DAF is a valuable national resource whose future applications will likely extend far beyond its original mission.

"DAF is the first facility of this complexity," sums up Livermore physicist Willy Cooper, Nevada Experiments and Operations Program Leader, "for handling unique and potentially hazardous nuclear weapons components and operations that DOE has brought online in several decades. With its 21st-century focus on environmental, safety, and health considerations, DAF is a functional testimony to the vision of the former generation of weapons scientists, valid today even with a shift in strategic national policy."

— Lori McElroy

Key Words: Device Assembly Facility (DAF), DOE, high explosives, Nevada Test Site, nuclear-explosive operations, nuclear weapon assembly and disassembly, stockpile stewardship, subcritical experiments.

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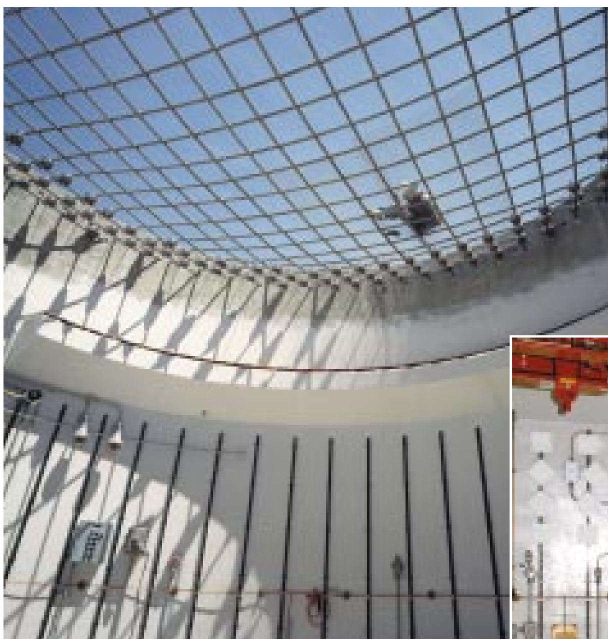

A "gravel gertie" assembly cell during and after construction. The assembly cells were designed to provide the utmost protection to the public, nearby workers, and the environment in the event of an inadvertent explosion.